Reduced to minimum cost: Lay-down heliostat with monolithic mirror-panel and closed loop control

Andreas Pfahl, Fabian Gross, Phillip Liedke, Johannes Hertel, Jens Rheinländer, Siddhant Mehta, Juan Felipe Vásquez-Arango, Stefano Giuliano, and Reiner Buck

Citation: AIP Conference Proceedings **2033**, 040030 (2018); doi: 10.1063/1.5067066
View online: https://doi.org/10.1063/1.5067066
View Table of Contents: http://aip.scitation.org/toc/apc/2033/1
Published by the American Institute of Physics

Reduced to Minimum Cost: Lay-Down Heliostat with Monolithic Mirror-Panel and Closed Loop Control

Andreas Pfahl[1, a)], Fabian Gross[1], Phillip Liedke[1], Johannes Hertel[1], Jens Rheinländer[1], Siddhant Mehta[1], Juan Felipe Vásquez-Arango[1], Stefano Giuliano[1], Reiner Buck[1]

[1]*German Aerospace Center (DLR), Pfaffenwaldring 38-40, 70569 Stuttgart, Germany.*

[a)]Corresponding author: Andreas.Pfahl@dlr.de

Abstract. A complete set of innovations are combined to a new heliostat of minimum cost. The main improvements are a monolithic sandwich-cantilever-arm concentrator of low material and fabrication cost, a lay down of the panels during storms to reduce the maximum wind loading of the structure, and a closed loop control to reduce the accuracy requirements on the mechanical components of the tracker. The design of the main heliostat components is described. The dimensioning of the heliostat is based on wind loads determined by wind tunnel tests. The resulting cost reduction and an outlook on possible modifications for further cost reduction is given.

INTRODUCTION

Solar tower plants with thermal storage have a cost advantage compared to PV with battery storage at high capacity factors (i.e. high number of storage hours). To keep this cost advantage in the future, the CSP costs have to be further decreased [1]. The Sunshot initiative demands heliostat field cost ≤75$/m² to reach LCOE of 6¢/kWh [2]. An impressive amount of different heliostat approaches already exists [3]. DLR developed with support of sbp-sonne, NEFF Gewindetriebe, and SOLTEC a new heliostat concept which enables to achieve the challenging cost target. A complete set of innovations leads to low cost of all heliostat components.

The DLR project KOSMOS develops the new heliostat concept for 50 m² size. A table-top model was built as a demonstrator and for first tests of the optical sensor control (tracking accuracy < 1mrad). A prototype of 9 m² has been designed and is under construction. The main design features and cost estimations are presented.

DESIGN

Overview

The main component of the heliostat (Fig. 1) is a monolithic sandwich concentrator which combines the advantages of cantilever-arm and sandwich structures and consists of a comparably low amount of parts [4]. The concept avoids the complexity of canting by forming only one single facet. Thin glass mirrors sandwiched with a back structure yield high reflectivity and slope accuracy and hence increased annual optical efficiency of +5% [5]. A simple carousel carriage with one actuated wheel realizes the azimuth movement. A low cost linear spindle actuator with the drive housed in the spindle passes through the panel’s centre and thus enables to use a simple two wheel carriage for the azimuth drive. The heliostat uses a control system with an optical sensor attached to the mirror panel for a closed-loop control of its orientation and compensates tracking errors which reduces the requirements on the accuracy of the mechanical components. Therefore, the carousel carriage may run on a simple track, which consists e.g. of stabilized soil or a simple concrete ring. The carriage is connected to the ground anchor which can be a pile

SolarPACES 2017
AIP Conf. Proc. 2033, 040030-1–040030-8; https://doi.org/10.1063/1.5067066
Published by AIP Publishing. 978-0-7354-1757-1/$30.00

driven into the ground. The wheels are weighted by concrete blocks or sand-filled containers to avoid slippage during high wind loads. For stow, the spindle drive pulls the panel to the ground onto the wheels and two extra supports. Thus, the panel is well protected during storms. The reduced wind loads relax requirements and cost for the cantilever-sandwich concentrator.

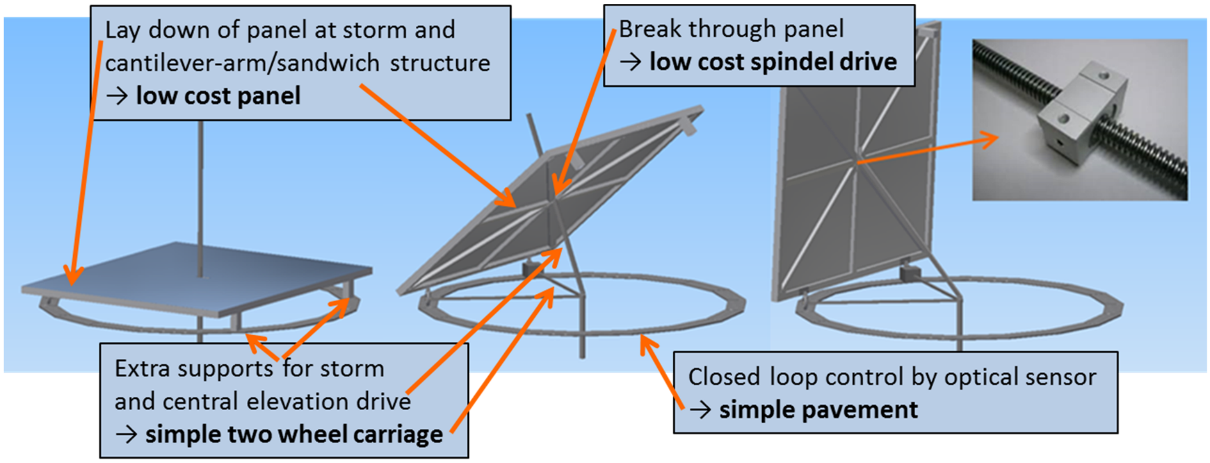

FIGURE 1. Heliostat concept for minimum cost of all components [6]

Concentrator

About 30-40% of the heliostat fields costs are related to the concentrator, comprising mirrors and support structure [7]. Hence, primarily the cost of the concentrator has to be reduced. In addition, the total effective field cost can be further reduced by increased concentrator efficiency.

Framework or I-beam cantilever arms are able to resist high loads at comparably low weight and cost (Fig. 2, left). When connected directly to the center, no torque tube is needed [8] and a particularly low cost back structure is obtained (Fig. 2, middle). The advantage of sandwich facets (Fig. 2, right) is the higher reflectivity of the thin glass mirrors and the better shape accuracy which lead together to 5% higher annual field efficiency [5]. However, current sandwich facets are significantly more expensive than standard mirrors.

FIGURE 2. Standard mirror support structures with cantilever arms and torque tube (left), with central mount of the cantilever arms (middle) and with sandwich structure (right)

The new solar concentrator approach combines the advantages of cantilever arms connected directly to the center (Fig. 2, middle) and of sandwich structures [9]. The framework cantilever arms as well as the support trusses are substituted by a sandwich structure with rigid foam core from polyurethane or extruded polystyrene for instance (Fig. 3).

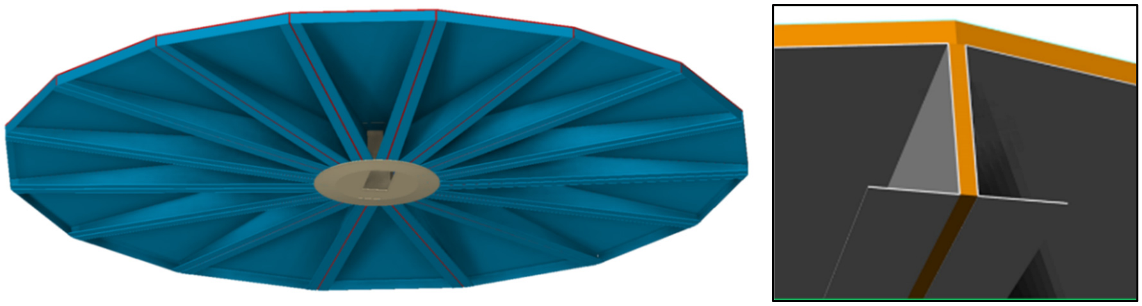

FIGURE 3. Solar concentrator with cantilever-arm-sandwich structure

The design allows an arbitrary mirror-area of about 8 m² to 50 m² [4] by adjusting the number and height of the beams. The height has a decisive effect on the optical quality. Regarding weight optimization with fixed total slope error (determined according to [10]) it is useful to increase the beam's height towards the center as deformation and stress analyses via FEM have shown (Fig. 4).

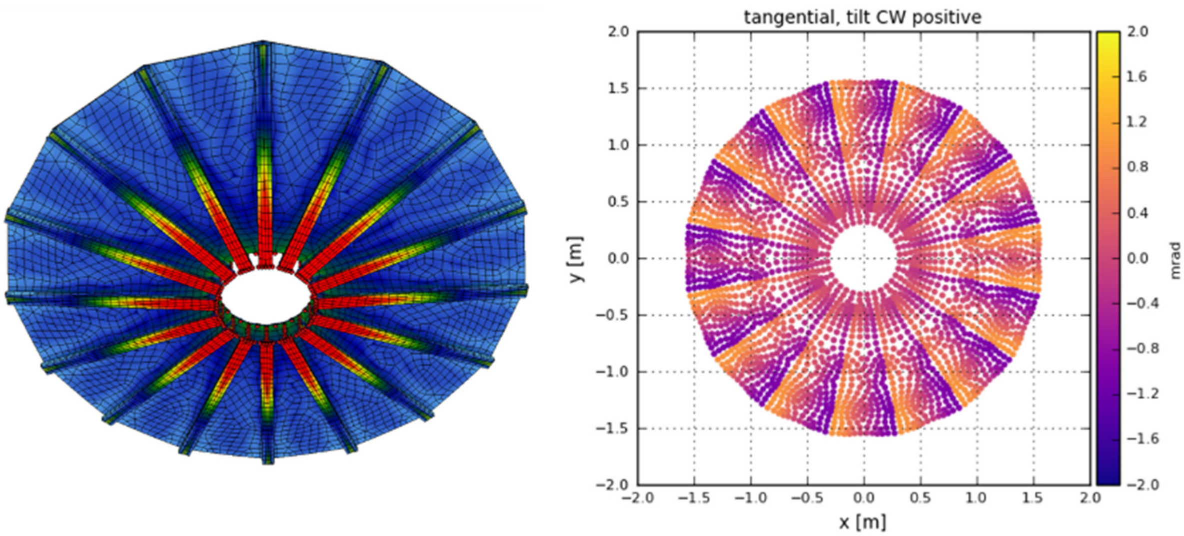

FIGURE 4. Maximum stress under gravity and storm wind loads (left) and shape accuracy under gravity and operational wind loads (right) determined via FEM

The monolithic cantilever-sandwich concentrator will be shaped by a large mold. A low cost mold can be realized by cement or a sand/loam mixture (may be stabilized with a vacuum membrane or injection of binders) formed to accurate shape by a laser-cut metal template that is rotated around a central pivot, defining a nominally parabolic surface with slight curvature, see Fig. 5 [11].

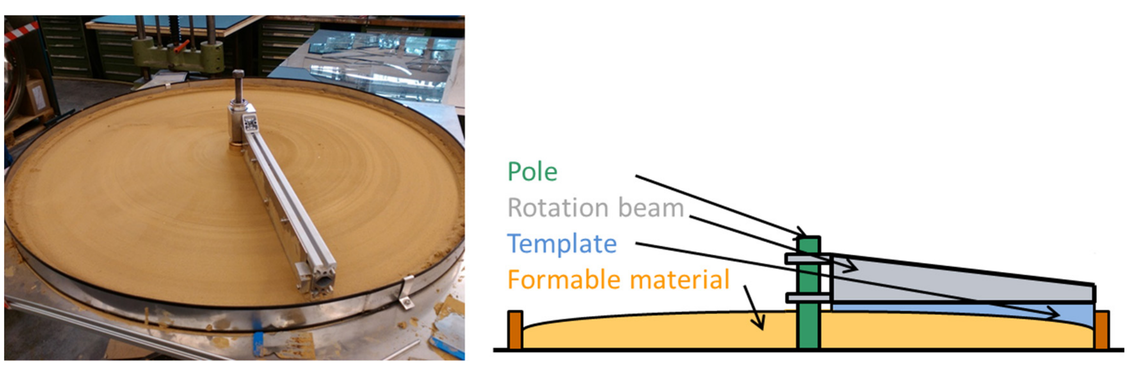

FIGURE 5. Manufacturing of large low cost mold by rotating template shaping a formable material

Azimuth Drive

The carousel drive consists mainly of two wheels running directly on a low cost concrete ring or just on stabilized soil. They are loaded by weights to avoid slippage at maximum wind loads (determined by the wind tunnel tests, compare §3). The weights may consist of simple concrete blocks or of containers filled with sand or stones available at site. The wheels are connected by two bars with the central bearing mounted on a pile which is driven into the ground as an anchor (Fig. 6, left). The two bars are loaded mainly by tensile and compression forces and only by comparably low bending moments which leads to small cross section/wall thickness and weight. The central bearing is close to the ground which avoids a costly pylon and reduces the bending moment on the ground anchor. The accuracy demands on the runway are low because closed-loop feedback control is implemented (compare §2.5). The long lever arm between wheels and central bearing is advantageous regarding tracking accuracy and torque of the drive unit. To further reduce the loads on the geared motor, an additional low cost reduction gear is foreseen (Fig. 6, right). The backlash of this chain gear is negligible when pre-tensioned [12].

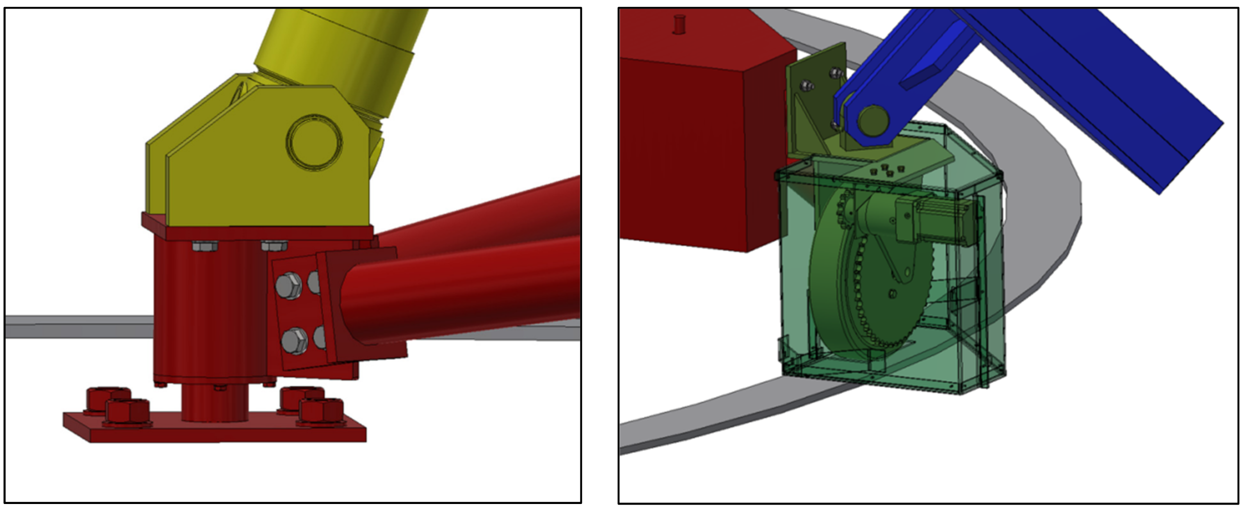

FIGURE 6. Central bearing (left) and encased and weighted driven wheel with chain reduction gear (right)

Elevation Drive

The spindle of the elevation drive passes through the center of the panel to enable a low cost two wheel carriage and to avoid an extensive scissor mechanism. The geared motor is housed in the spindle to achieve a compact design which allows a low height of the concentrator in stow and to avoid an extra housing for the drive unit [13]. An encasement of the spindle is needed only above the concentrator. Below the concentrator, dust particles can be swept away from the spindle by ring brushes. During heavy sand storms, the concentrator is in parallel to ground with the spindle completely covered by the (upper) encasement. For the spindle encasement of the first prototype a conventional rubber bellow is used. Several approaches for cheaper systems with less shading were found and will be developed in a following step.

Control

The closed loop control has the task to ensure good tracking accuracy (< 1 mrad) by compensating errors due to reduced requirements on mechanical parts of the tracker. This simplifies manufacturing and installation and reduces cost. Systematic errors other than back lash can be offset within the measurement accuracy of the camera system. The optical sensor prototype consists of a 18 MPix camera together with a 1.78 mm equidistant fisheye lens.

The working principle is shown in Figure 7 (left) [14]: the camera is fixed to the concentrator and performs the same rotations as the mirror. The sensor detects markers with known 3D-position like the sun and features of the receiver/tower. For a camera with internal as well as external calibration with respect to the mirror, the algorithm reconstructs the pose (position and orientation) of the camera and hence of the mirror. Deviations from the desired orientation are controlled by moving the two drives. Figure 7 (right) shows the perspective of a fisheye camera which is not pointing between the Sun and the receiver and triggers heliostat motion.

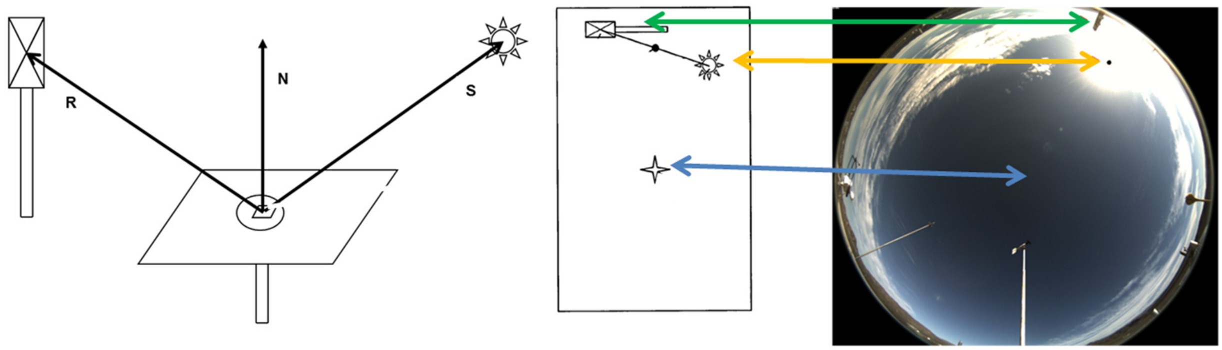

FIGURE 7. Working principle of optical sensor: it moves with the heliostat and registers the orientation with respect to the surroundings, e.g. Sun and tower.

Since the radiance of the Sun (~1.5E+7 W/m²/sr through Earth's atmosphere) is 5E+4 higher than the radiance of Lambertian white surface reflecting 1 kW/m² (3E+2 W/m²/sr), the camera needs an extreme dynamic range to capture both the Sun and the surroundings. We use a Sun filter foil of optical density 3.8 (1:6300) which gives a clear Sun image for an exposure of 0.03 ms and the tower for an exposure of 900 ms (Fig. 8). The images are taken right one after another to represent a common pose of the heliostat. Hence, the minimum time between two consecutive pictures is in the range of 1 s. All in all a tracking accuracy similar to conventional heliostats is expected.

FIGURE 8. The Sun (left, 0.03 ms) has an apparent diameter of 14 pix/10 mrad. The cross section of the receiver (middle, 900 ms) is also 14 pix for a heliostat on the fringe of the field. Both objects are extracted with openCV (e.g. Canny, Shi-Tomasi on the right). With identification and reconstruction in the subpixel range a tracking accuracy of <1 mrad is expected

The prototype will be tested together with the heliostat under construction at the Solar Tower Jülich. Then an industrialization is planned which will reduce the price for the optical sensor possibly with consumer grade multi eye cameras and an integrated housing which simplifies cleaning.

DIMENSIONING

According to many studies the cost optimum heliostat size is in the range of 50 m² [3]. After the detailed development and the manufacturing process of a first prototype the optimum size for this specific heliostat design can be refined. For cost and handling reasons, a 9 m²-prototype will be built first with elevation drive and carriage already dimensioned according to the requirements of the (later) 50 m²-heliostat (Fig. 9).

FIGURE 9. 50 m²-heliostat (left) and small 9 m²-heliostat prototype with components dimensioned already for 50 m² (therefore spindle and carriage appear large) (right)

The reduced wind loads at stow due to the lay down option were determined by wind tunnel tests (Fig. 10) and served as base for the dimensioning of the heliostat structure via FEM. The deposit of dust and sand on the mirror is higher for the mirror panel close to the ground. Therefore, the heliostat is stowed usually with upright panel and is laid down only for high wind speeds.

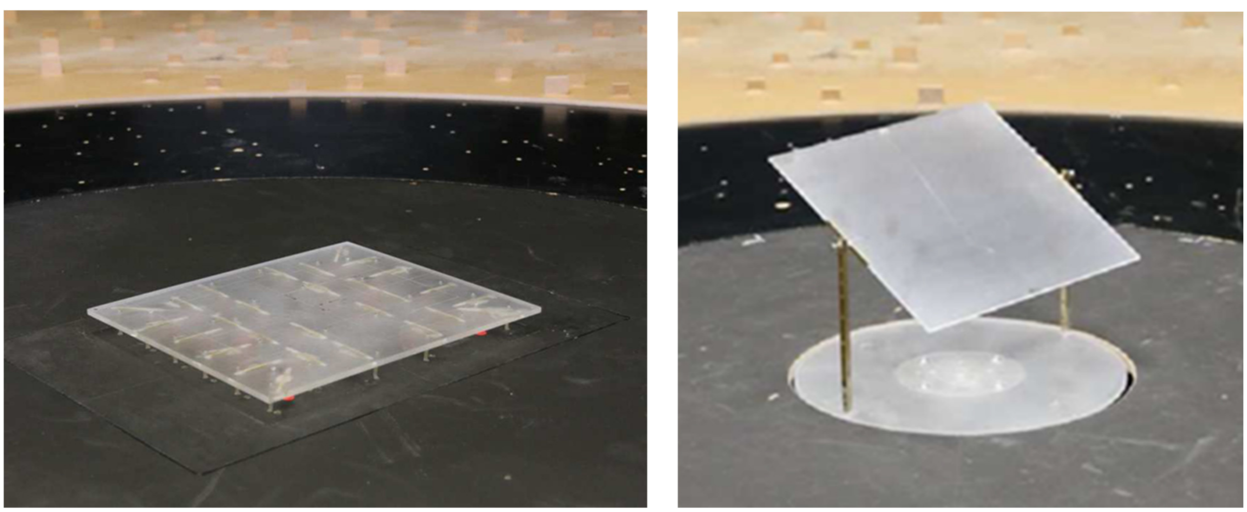

FIGURE 10. Wind tunnel tests for lay-down heliostat with elevation axis at lower edge (left) and thus reduced wind loads for stow compared to conventional heliostats with central elevation axis (right)

COST

The innovations and resulting cost targets for a 10'000 heliostats field are listed for each part (according to first prototype design) in Table 1. The current heliostat cost assumptions are based on personal communications with heliostat suppliers. An extraordinary high local content is possible because drives are neither highly loaded nor need to be very precise. Main possibilities for further cost reduction below 80 $/m² are the following:

- Substitution of bellow for spindle protection by simpler solution (several approaches already proposed)
- Stabilized soil for the runway instead of concrete ring and adapted wheels
- Simplification of wheel housing
- Cheaper weights
- Industrialized sensor system

TABLE 1. Set of innovations and estimated heliostat field cost reduction for 10'000 heliostats of 50 m²

Part	**Innovation**	**Current Cost** ($/m²)	**Reduced Cost** ($/m²)
Mirror panel	Lay-down for stow Monolithic cantilever-sandwich panel [9] Low-cost large-size mold [11]	50	30
Azimuth drive (carousel carriage) incl. ground preparation	Simple pavement or compact ground with central ground anchor sufficient due to closed loop control Low cost 2-wheel carriage sufficient due to central elevation drive and panel supports for stow Weighted wheel drive	23	17
Elevation drive (spindle)	Direct spindle drive through central opening in panel Drive housed in spindle [13]	11	8
Control/ field cabling	Closed loop control by optical sensor to allow for low precision of mechanical tracking [14]	12	14
Fabrication/instal-lation/profit (10%)		24	21
Total cost		120	**90**
Efficiency	5% higher efficiency of mirror, -1% shading by spindle	-	-4
Effective cost		120	**86**
Further reduction	Simplified runway, spindle protection, wheel housings, weights		
Cost outlook			**<80**

SUMMARY AND OUTLOOK

A new heliostat design for minimum cost is under development. The concentrator combines the advantages of cantilever arm and sandwich structures and leads to 5% higher field efficiency. It can be laid down for storm events to reduce the maximum wind loading. The elevation drive passes through the panel which leads to less than 1% shading losses, but significantly simplifies the design of it and of the azimuth drive which is realized by a two wheel carriage with one driven wheel weighted against slippage and running directly on stabilized soil or on a simple pavement. Only low accuracy demands on the mechanical parts are required due to a closed loop control by means of an optical sensor which detects the position of the Sun and of reference points of the surrounding. The dimensioning of the heliostat via FEM is based on wind tunnel tests.

Although the cost optimum size is presumably in the range of 50 m², at first only 9 m² heliostat prototypes will be realized for cost and handling reasons in the DLR project "KOSMOS" and by several Moroccan industrial consortia in the project "HelioMaroc" supported by the Federal Foreign Office. With the experiences gained from the tests of the prototypes a 50 m² heliostat should be developed which should include approaches for further reduced cost like simplification of runway, spindle protection, wheel housings, and weights. Cost estimations based on the current design lead to 86 $/m² total heliostat field cost. With the further approaches for cost reduction, cost < 80 $/m² seem realistic which is close to the Sunshot initiative demands for LCOE of 6¢/kWh [2]. Further partners for these developments are sought-after.

ACKNOWLEDGMENTS

The authors thank the Technology Marketing of DLR for its support, the Federal Ministry for Economic Affairs and Energy (BMWi) for its financial support of the sandwich panel development (project "SPACE", code 0324071), and the Federal Foreign Office for the support of the project "HelioMaroc".

REFERENCES

1. M. Engelhard, et al., "Techno-Economic Analysis and Comparison of CSP with Hybrid PV-Battery Power Plants - Results from the THERMVOLT Study", SolarPACES 2016 conference, Abu Dhabi, UAE.
2. J. Gary, C. Turchi, N. Sieger, "CSP and the DOE Sunshot Initiative", Proc. SolarPACES 2011 conference, Granada, Spain.
3. A. Pfahl, J. Coventry, M. Röger, F. Wolfertstetter, F. Vasquez, F. Gross, M. Arjomandi, P. Schwarzbözl, M. Geiger, P. Liedke, "Progress in Heliostat Development. Solar Energy", Solar Energy 152, 2017, 3-37.
4. O. Siegmeier, "Entwurf und Strukturoptimierung einer neuartigen Sandwichfacette für Heliostate", master thesis, sbp-sonne, Technical University Berlin, 2017.
5. C. Holze, H. Brüggen, R. Misseeuw, B. Cosijns, R. Albers, D. Isaza, R. Buck, A. Pfahl, Laminated Solar Thin Glass Mirror Solution for Cost Effective CSP Systems, SolarPACES 2012 conference, Marrakesh, Morocco, September 11-14.
6. A. Pfahl, R. Buck, P. Liedke, F. Gross, "Solar Device", international patent WO 2016202941 A2, 2016.
7. A. Pfahl, "Survey of Heliostat Concepts for Cost Reduction", Solar Energy Engineering 2014, 136.
8. F. von Reeken, G. Weinrebe, M. Balz, "Special Stiffness Requirements of Heliostats for Regions With High Operational Wind Speeds", SolarPACES 2016 conference, Abu Dhabi, UAE.
9. O. Siegmeier, et al.. "Facette für einen Heliostat in Sandwich-Bauweise und Verfahren zum Herstellen einer Facette", patent pending, 2017.
10. L. Muschalski, "Auslegung einer Sandwich-Spiegelfacette für Heliostate", bachelor thesis, DHBW, DLR, Stuttgart, Germany, 2016.
11. A. Pfahl, R. Buck, F. Gross, "Solarvorrichtung, Verfahren zur Herstellung eines Formteils und Verfahren zur Herstellung eines Formgebungselements", German patent application 102016210569.8, 2016.
12. P. Liedke, A. Lewandowski, A. Pfahl, E. Hölle, "Precise Low Cost Chain Gears for Heliostats", SolarPACES 2015 conference, AIP Conference Proceedings 1734, 020014 (2016); https://doi.org/10.1063/1.4949038.
13. A. Ries, "Linearantrieb mit einer Spindel", German patent application 10 2017 001 550.3, 2017.
14. A. Pfahl, R. Buck, K. Rehschuh, "Method for Controlling the Orientation of a Heliostat on a Receiver, Heliostat Apparatus and Solar Power Plant", international patent WO2008/058866A1, 2008.